60 Years

IAEA Atoms for Peace and Development

Basics of nuclear data: Radiation, radioactivity and nuclear reactions and their applications

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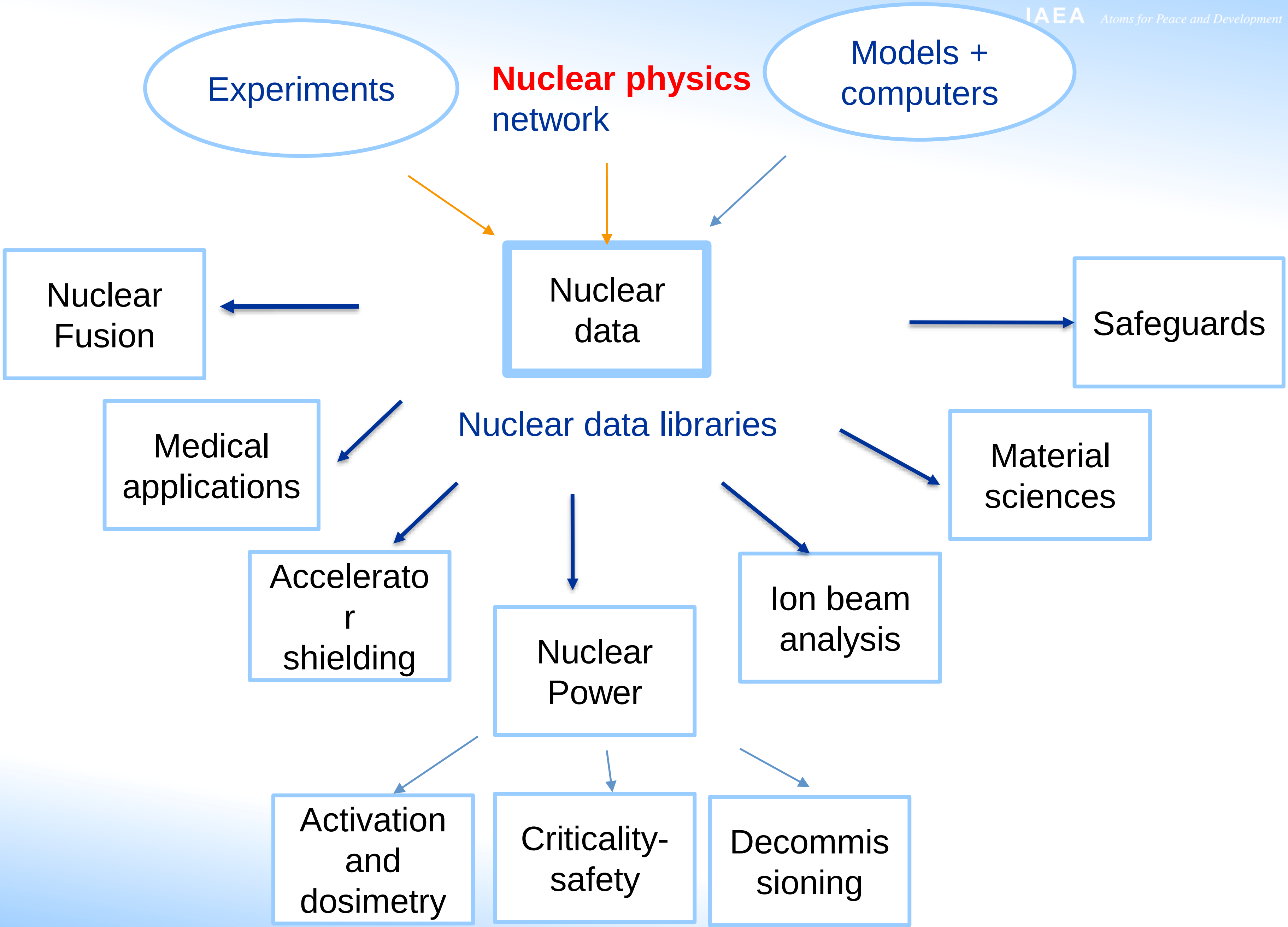
Presentation objectives.
Takeaways:

- All nuclear applications rely on basic nuclear data for nuclear reactions and nuclear structure
- Different types of radiation and nuclear decay
- Nuclear reactions can be simulated with the TALYS nuclear model code
- Most important applications: nuclear power reactors, nuclear fusion, medical isotope production, astrophysics.



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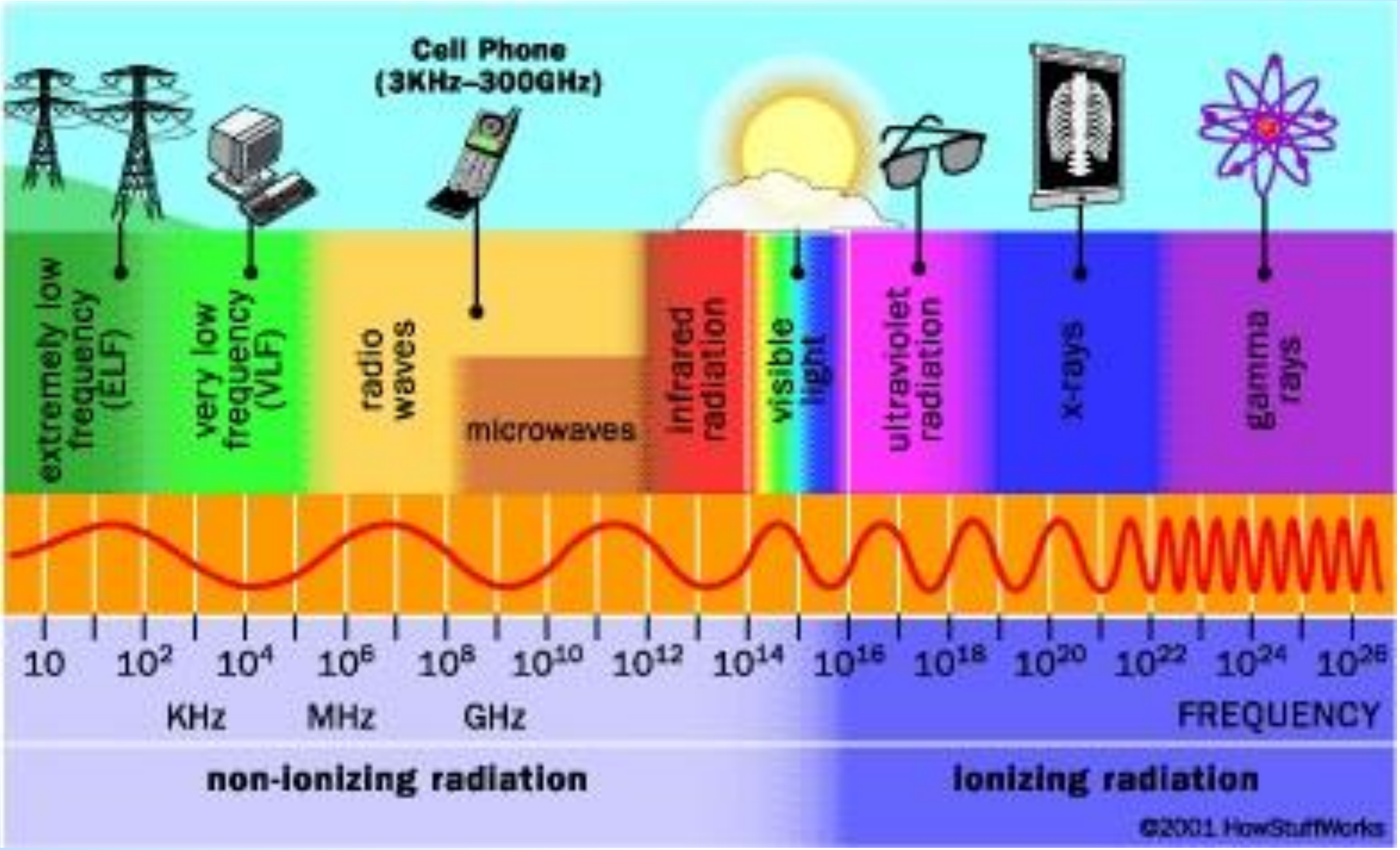
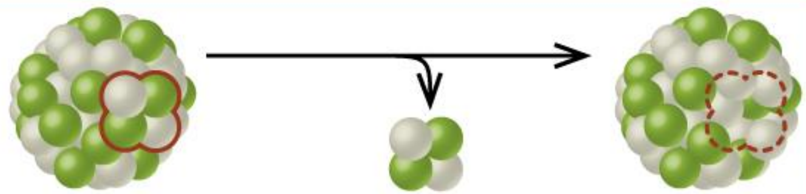
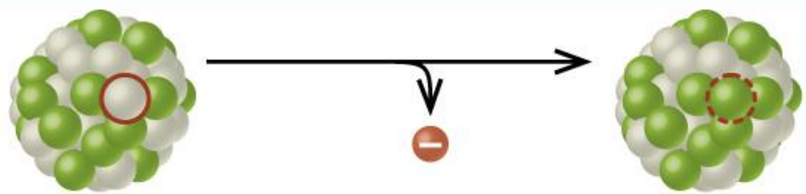
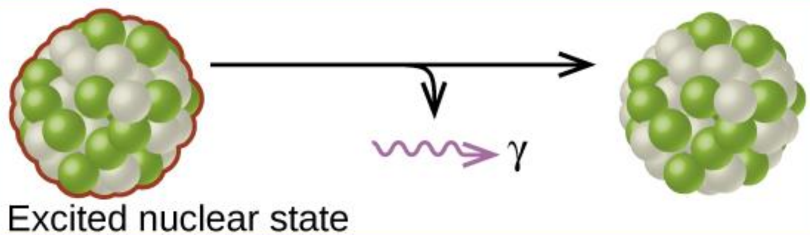
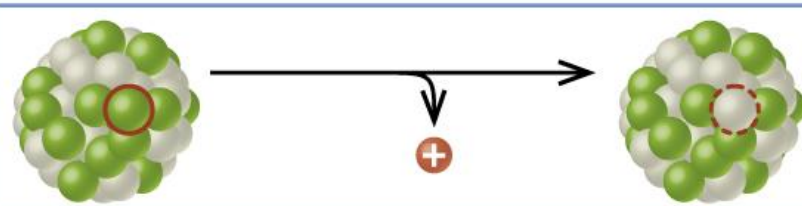
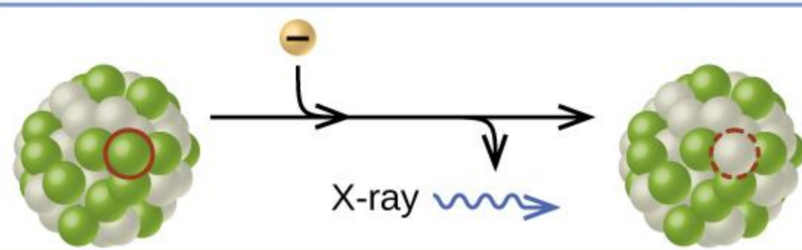
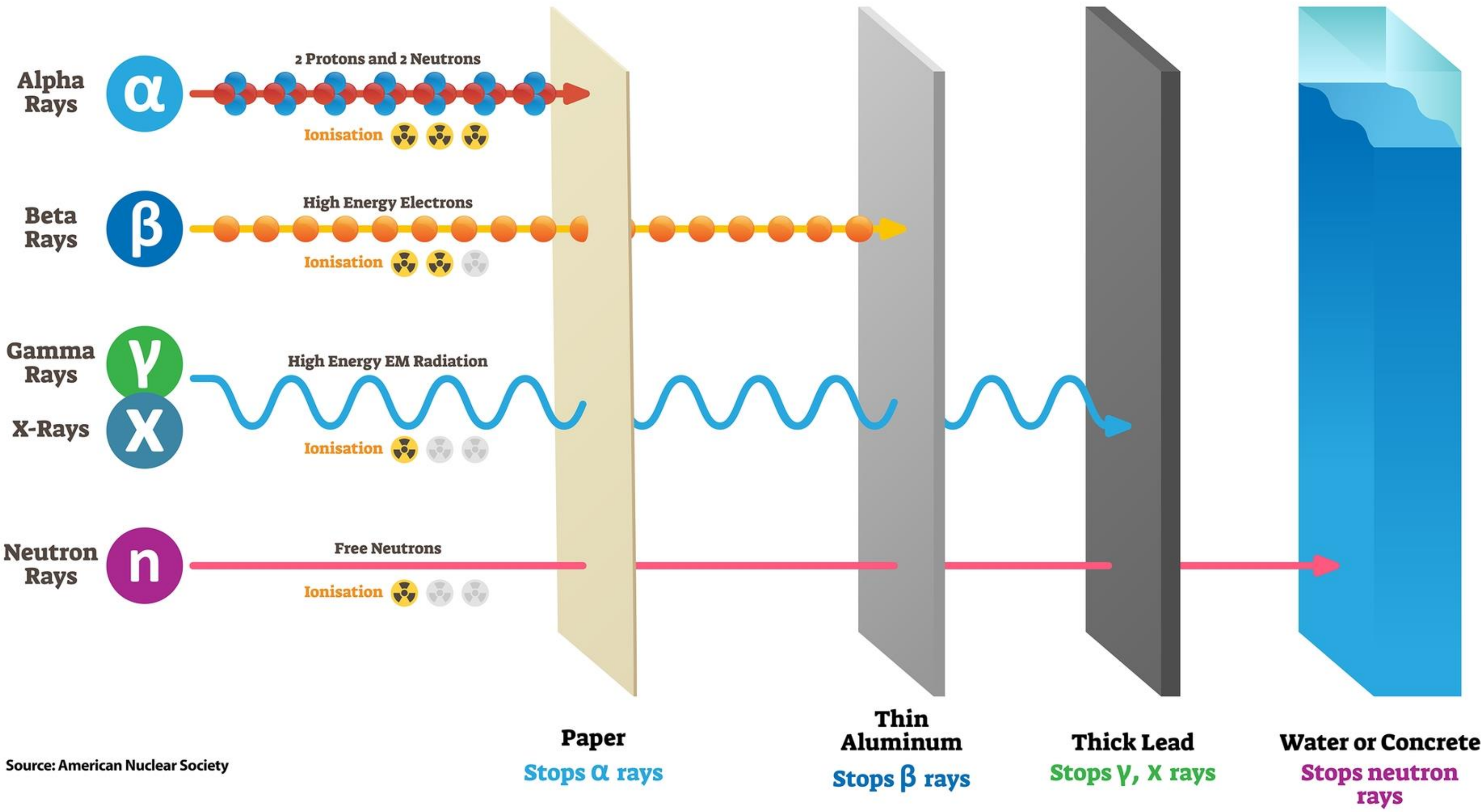
Types of radiation



Decay of an excited nucleus

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}X$ $\quad ^{4}_{2}He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}X$ $\quad ^{0}_{-1}e + ^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}X$ $\quad ^{0}_{0}\gamma + ^{A}_{Z}Y$		A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}X$ $\quad ^{0}_{+1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}X$ $\quad ^{0}_{-1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

TYPES OF RADIATION



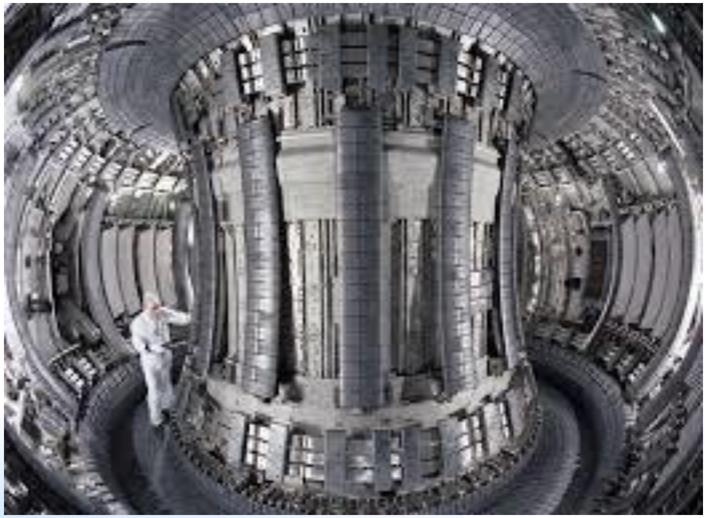
Source: American Nuclear Society

Nuclear reactions have/will change(d) the world

Nuclear weapons

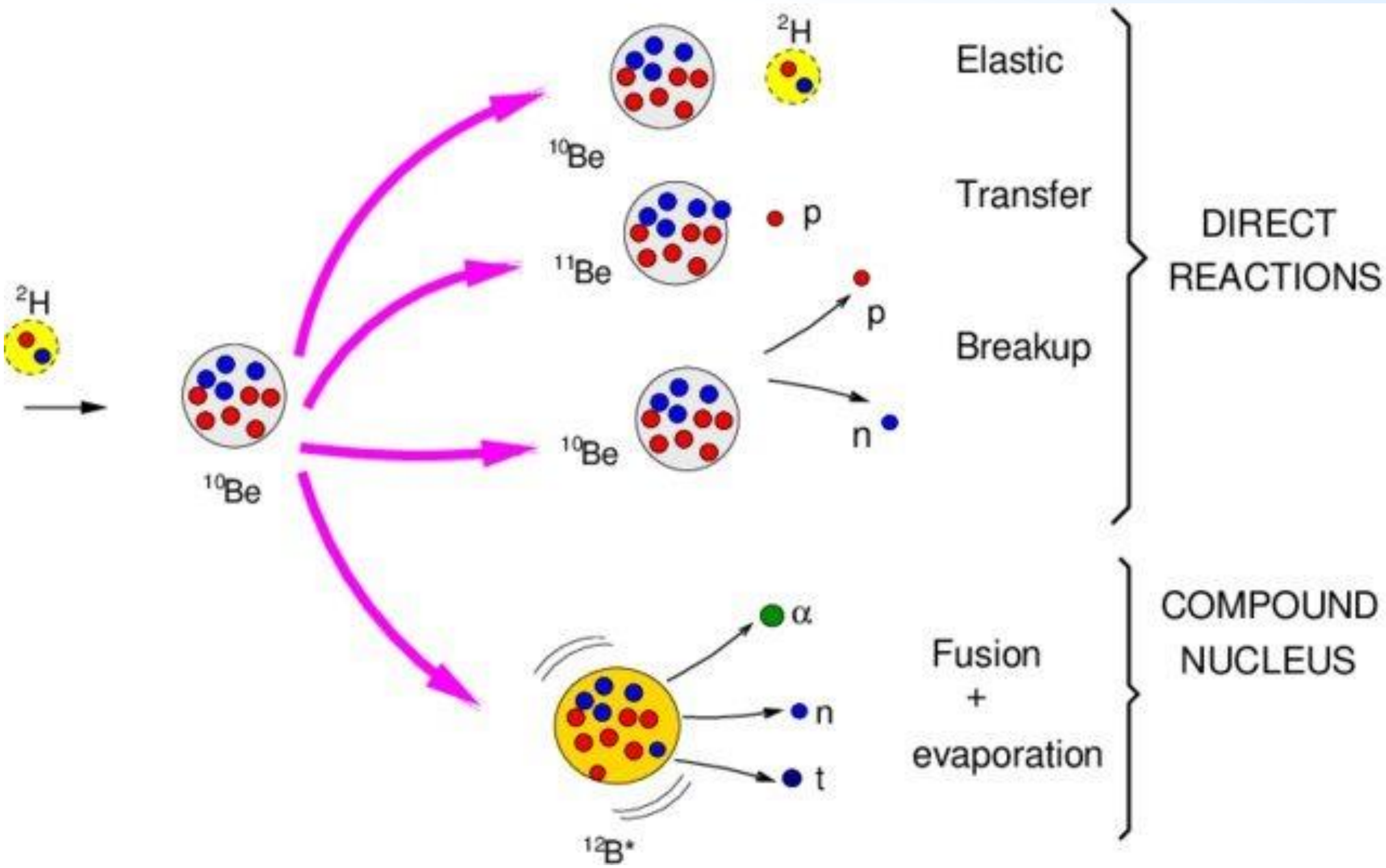
Nuclear energy

Medical isotopes



Nuclear fusion

Nuclear reaction



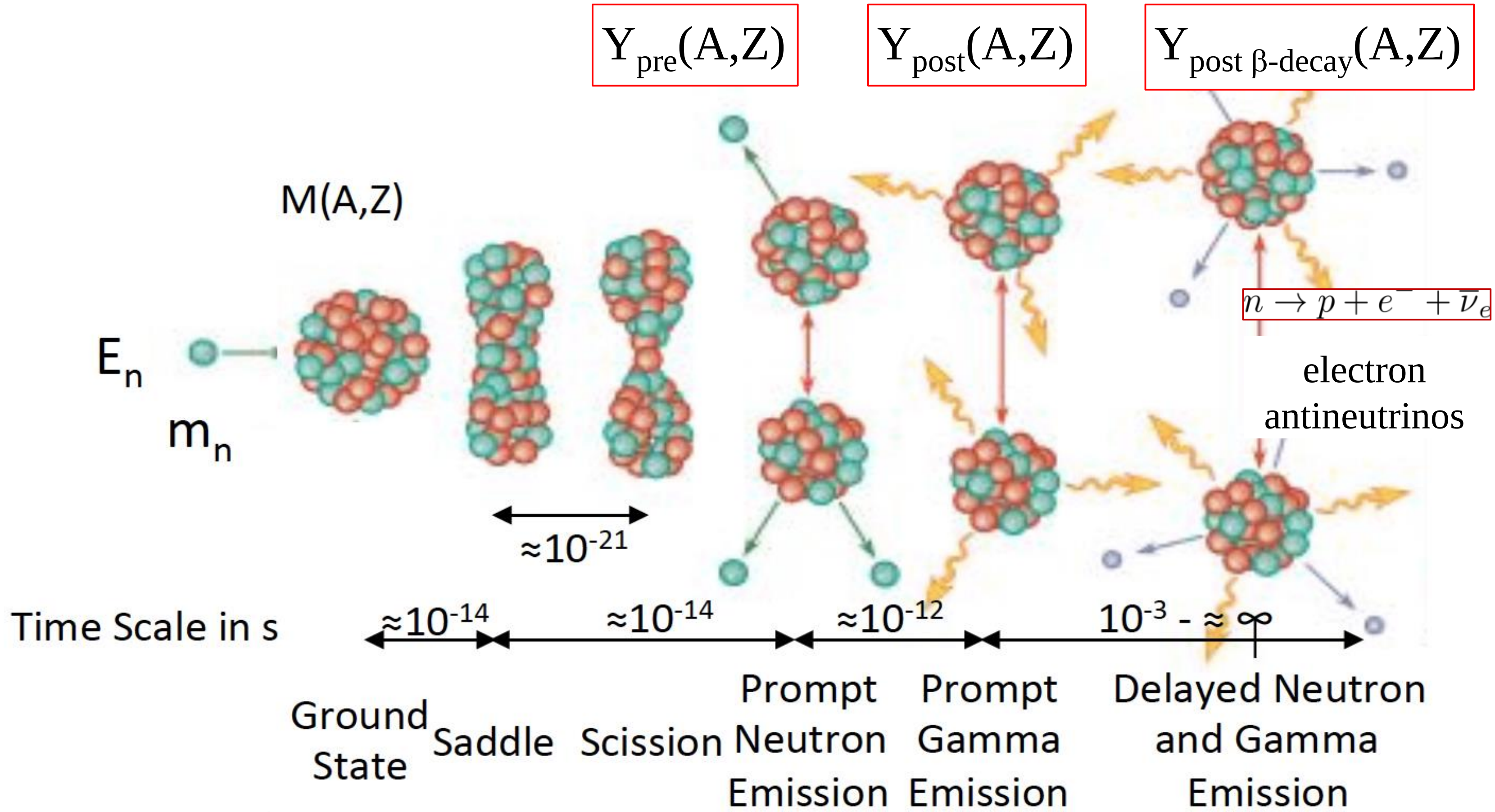
Fast: 10^{-21} sec

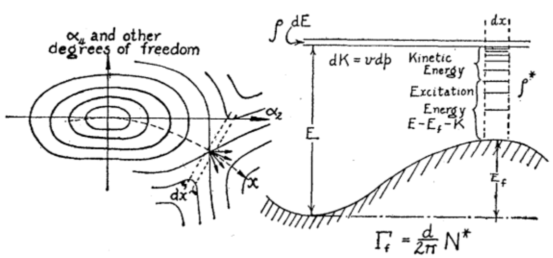
Slow: 10^{-16} sec

Analysis 1: Measurements

Analysis 2: Theory and computational simulation

The Fission Process





Pre-scission physics

IFY
(Independent Fission Yields)

→

CFY
(Cumulative Fission Yields)

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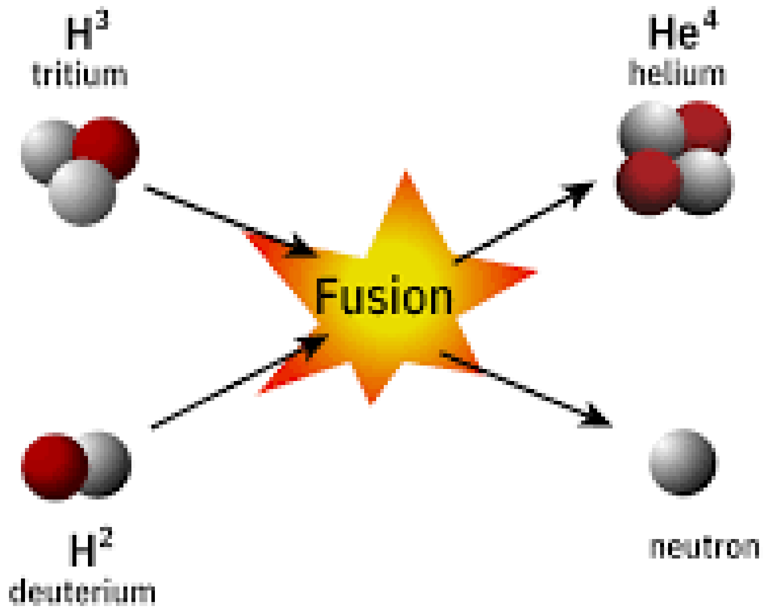
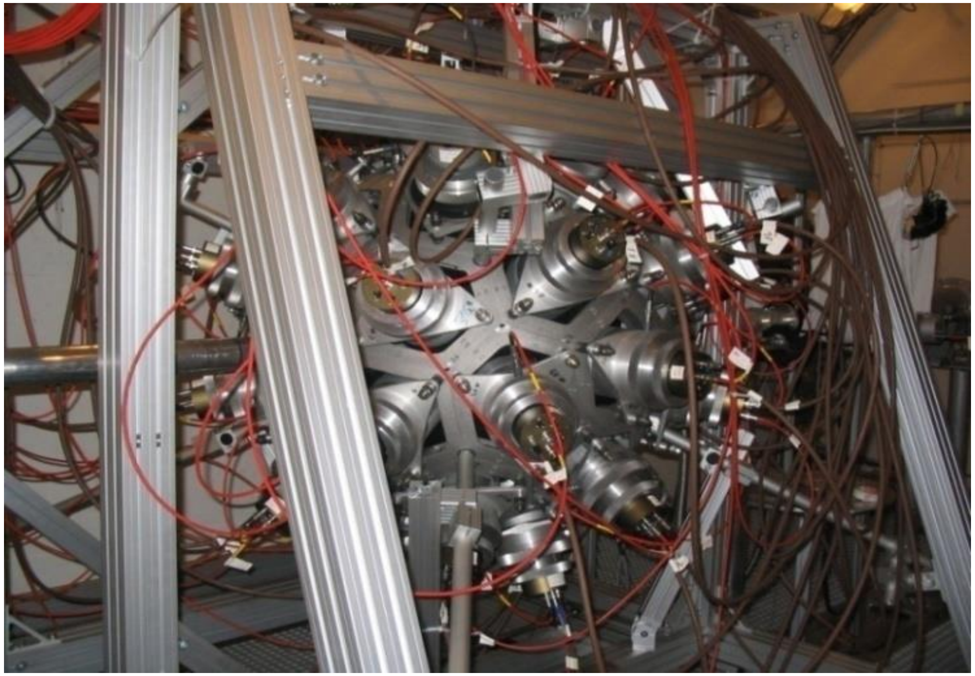
The future: Nuclear fusion

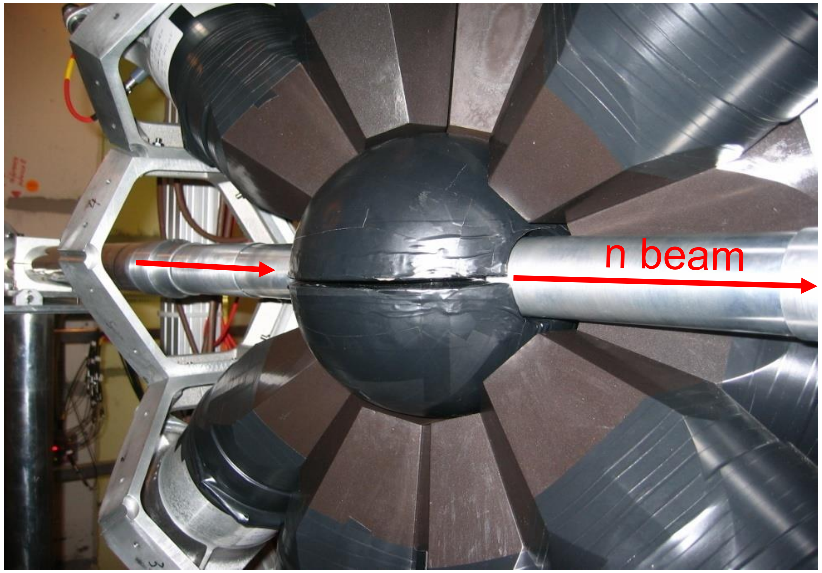


Like fission: release of energy
However: no long-lived fission products

Nuclear reaction measurements

Total absorption detector at n_TOF (CERN)





EXFOR database
(Nuclear Reaction Data Center Network: IAEA, NNDC, NEA, JAEA, etc)

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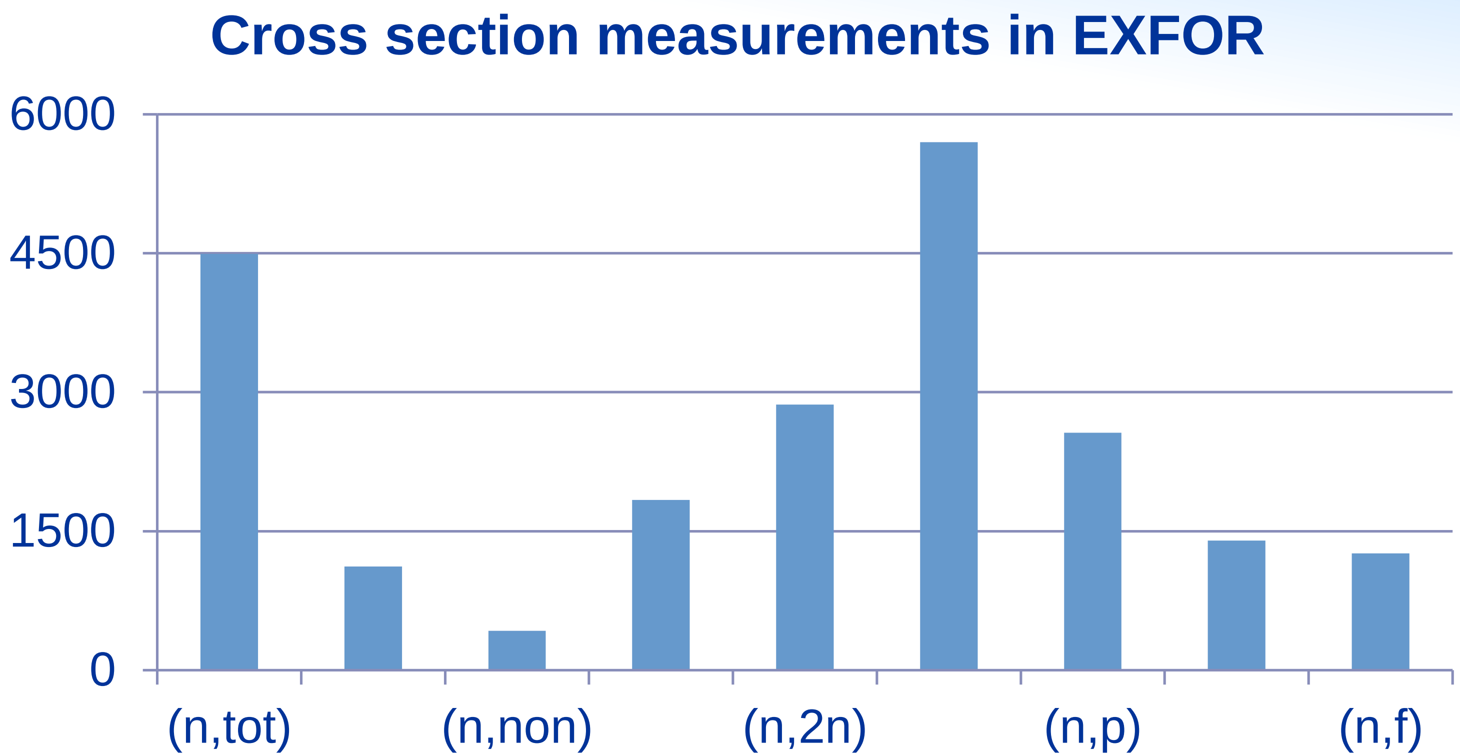


Total estimated cost of EXFOR (private comm.): between 20 – 60 Billion USD
Total estimated value of EXFOR : priceless

How do we calculate this with theory?

The compound nucleus formula for the binary cross section is given by

$$
\begin{aligned}
\sigma^{comp}_{\alpha\alpha'} &= D^{comp}\frac{\pi}{k^2}\sum_{J=mod(I+s,1)}^{l_{max}+I+s}\sum_{\Pi=-1}^{1}\frac{2J+1}{(2I+1)(2s+1)}\sum_{j=|J-I|}^{J+I}\sum_{l=|j-s|}^{j+s}\sum_{j'=|J-I'|}^{J+I'}\sum_{l'=|j'-s'|}^{j'+s'} \\
&\times\ \delta_\pi(\alpha)\delta_\pi(\alpha')\frac{T^J_{\alpha l j}(E_\alpha)\left\langle T^J_{\alpha' l' j'}(E_{\alpha'})\right\rangle}{\sum_{\alpha'',l'',j''}\delta_\pi(\alpha'')\left\langle T^J_{\alpha'' l'' j''}(E_{\alpha''})\right\rangle}W^J_{\alpha l j \alpha' l' j'},
\end{aligned}
\tag{13.2}
$$

Compound nucleus formula to simulate a nuclear reaction with the TALYS computer program

TALYS nuclear model code

Main developers: Arjan Koning (IAEA), Stephane Hilaire (CEA-DAM), Stephane Goriely (U

- Simulates a nuclear reaction
  projectiles : n,p,d,t,^{3}he, ^{4}he and gamma
  targets : $3 \leq Z \leq 124$ or $5 \leq A \leq 339$ (either isotopic or natural)
- Incident projectile energy from a few keV up to 200 MeV
  (code "works" up to1 GeV)

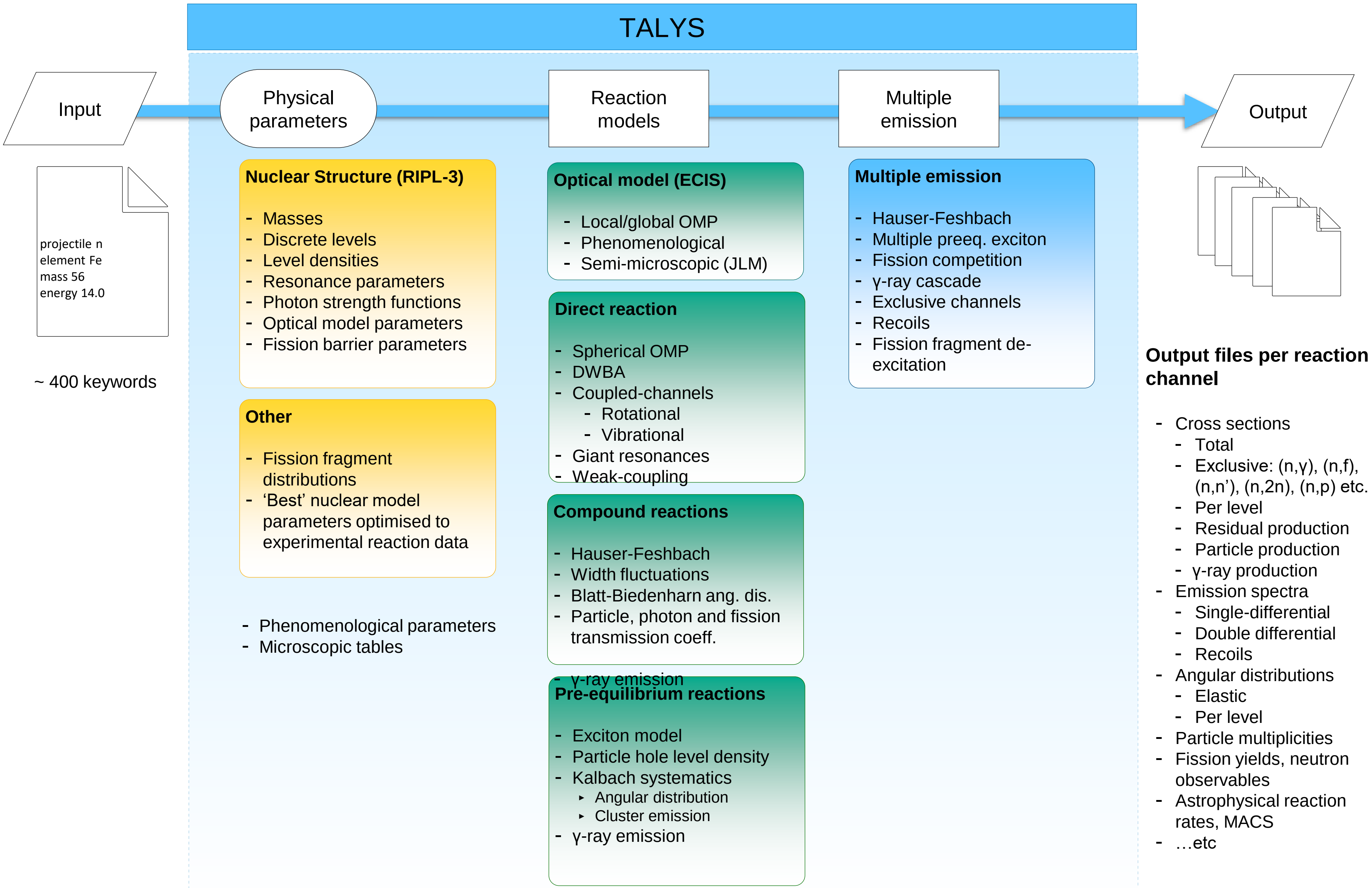
- TALYS can be used:

  . In depth single reaction analysis

  . Global nuclear reaction network calculation (eg astrophysics)

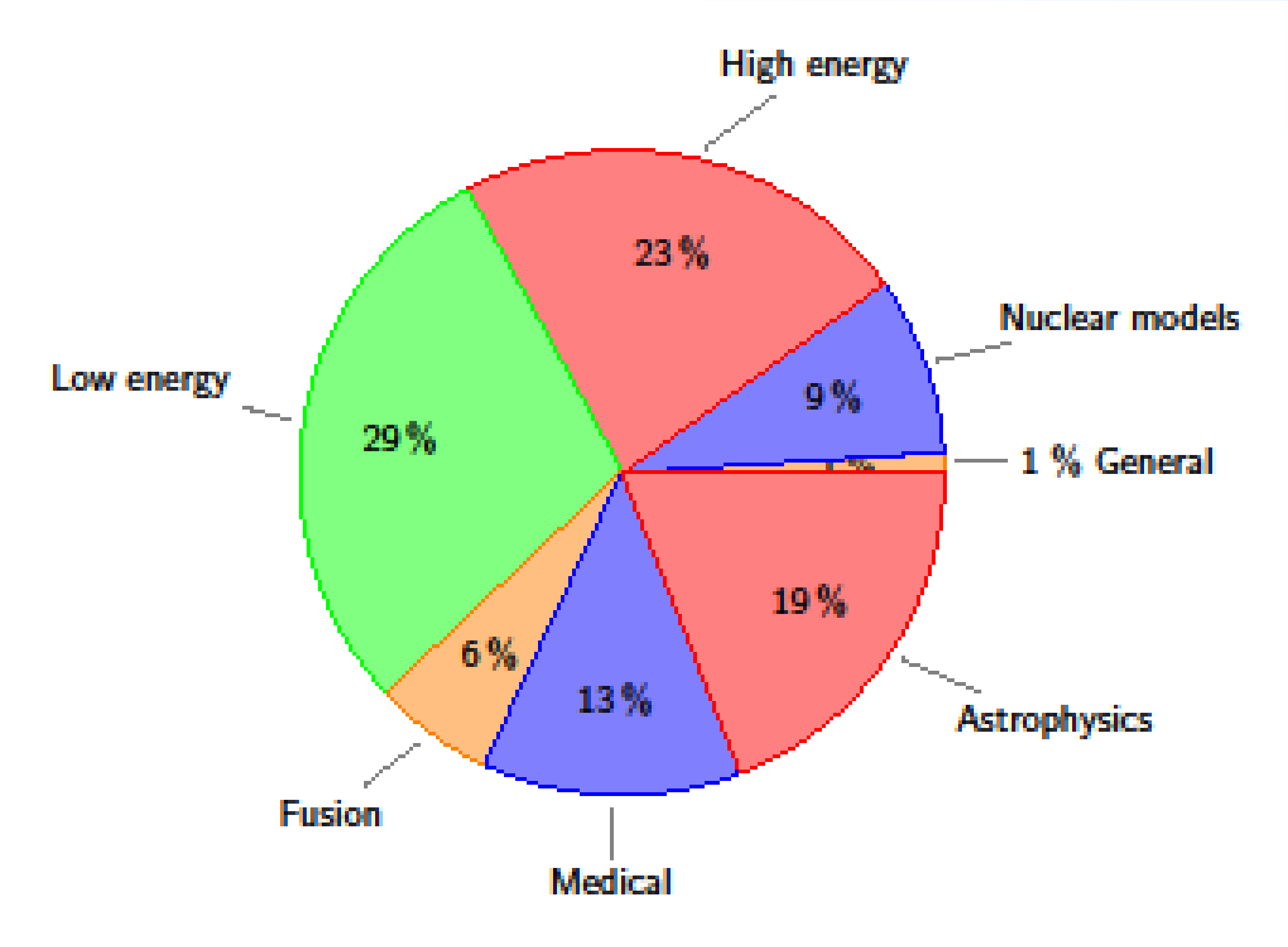
  . Within a more global code system (nuclear data libraries, reactor physics)

TALYS is always under development, while a stable version is released every 2 years. www.talys.eu


TALYS
Input
projectile n
element Fe
mass 56
energy 14.0
~ 400 keywords
Physical parameters
Reaction models
Multiple emission
Output
Nuclear Structure (RIPL-3)
- Masses
- Discrete levels
- Level densities
- Resonance parameters
- Photon strength functions
- Optical model parameters
- Fission barrier parameters
Other
- Fission fragment distributions
- 'Best' nuclear model parameters optimised to experimental reaction data
- Phenomenological parameters
- Microscopic tables
Optical model (ECIS)
- Local/global OMP
- Phenomenological
- Semi-microscopic (JLM)
Direct reaction
- Spherical OMP
- DWBA
- Coupled-channels
- Rotational
- Vibrational
- Giant resonances
- Weak-coupling
Compound reactions
- Hauser-Feshbach
- Width fluctuations
- Blatt-Biedenharn ang. dis.
- Particle, photon and fission transmission coeff.
- γ-ray emission
Pre-equilibrium reactions
- Exciton model
- Particle hole level density
- Kalbach systematics
Angular distribution
Cluster emission
- γ-ray emission
Multiple emission
- Hauser-Feshbach
- Multiple preeq. exciton
- Fission competition
- γ-ray cascade
- Exclusive channels
- Recoils
- Fission fragment de-excitation
Output files per reaction channel
- Cross sections
- Total
- Exclusive: (n,γ), (n,f), (n,n'), (n,2n), (n,p) etc.
- Per level
- Residual production
- Particle production
- γ-ray production
- Emission spectra
- Single-differential
- Double differential
- Recoils
- Angular distributions
- Elastic
- Per level
- Particle multiplicities
- Fission yields, neutron observables
- Astrophysical reaction rates, MACS
- …etc

Use of TALYS

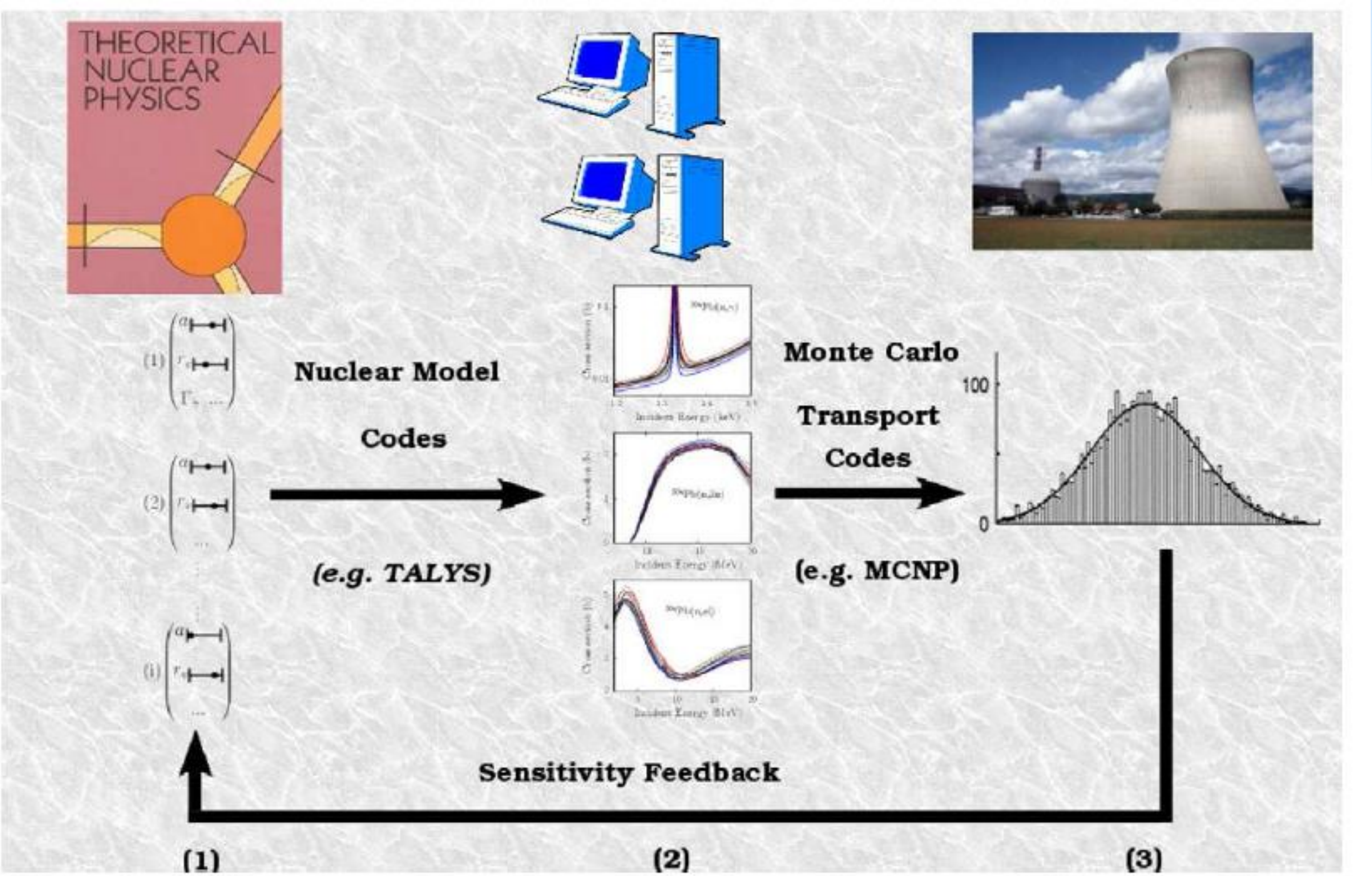
~6000 different citations



TALYS for astrophysics (~1000 papers)

- Nucleosynthesis
- Cosmic rays
- Solar flares (gamma rays)
- Neutron star (mergers)
- Cosmogenic production
- Analysis of dark matter experiments
- Black holes
- Re-Os chronology
- Solar system abundance
- etc.

From nuclear data to reactors



A.J. Koning and D. Rochman, ``Towards sustainable nuclear energy: Putting nuclear physics to work'', Ann. Nuc. En. 35, p. 2024-2030 (2008).

Looping over nuclear science

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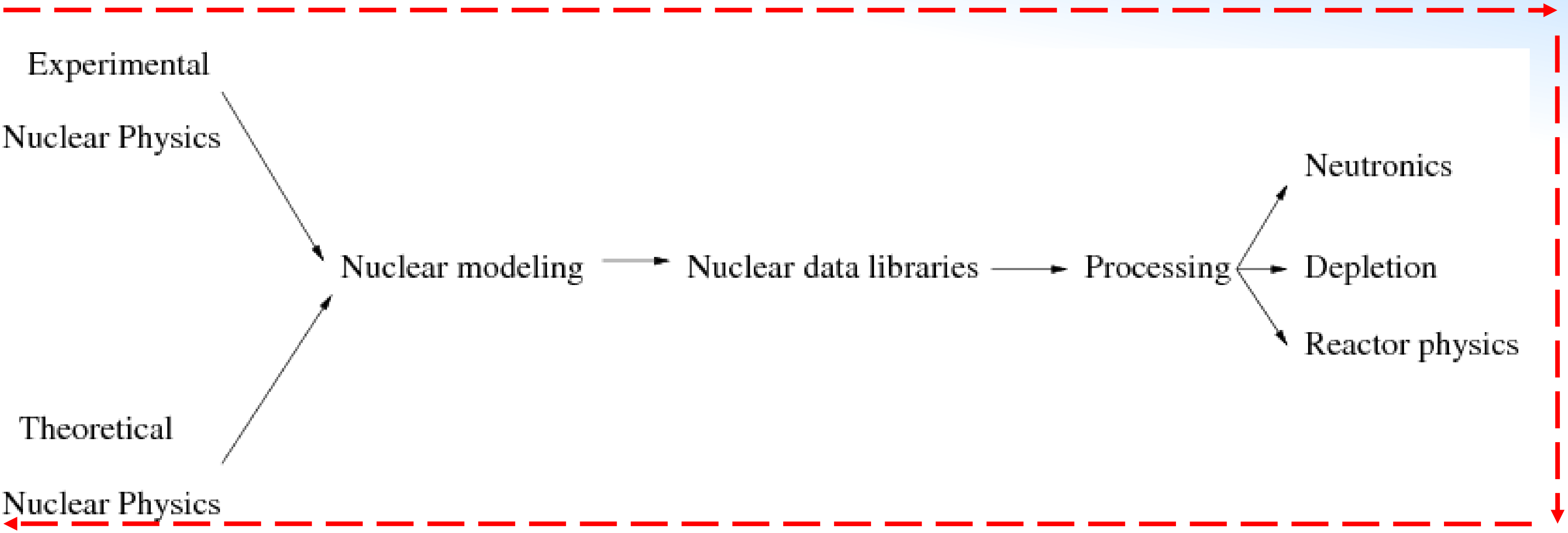
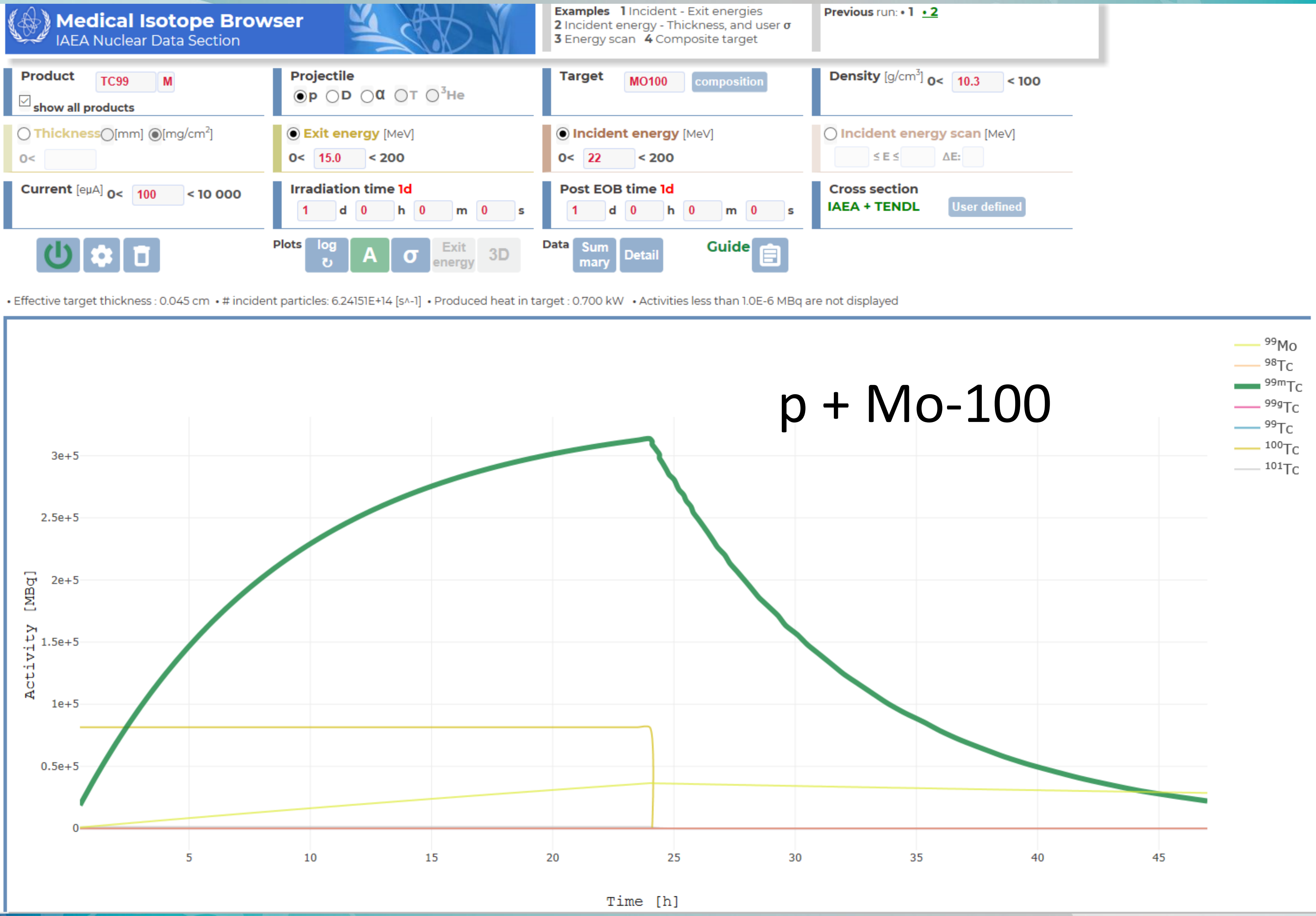


Feedback, sensitivity, uncertainty propagation, …..

Road to success:

- Use (extremely) robust software
- Store all human intelligence in input files and scripts
- Rely on reproducibility and quality assurance
- Attempt to make the step towards artificial intelligence

Medical isotope browser: nds.iaea.org/mib



Upcoming Workshops/Schools

- Simulation of nuclear reaction data with TALYS, ICTP, Trieste, Italy, preliminary dates Oct 9-13 2023
- TALYS school, Wits Rural Campus, South Africa. Organisation: Univ of Oslo (Nor) /Ithemba (SA) Preliminary dates: Nov 12-25, 2023

Summary and final thoughts

- “Basic nuclear science”: the knowledge of the structure of an atomic nucleus and its interaction with particles
  - Combination of quantum physics and statistical physics
  - Both experimental physics and theoretical/computational physics are always necessary to improve our knowledge
- Better nuclear data:
  - Better knowledge of nuclear reactions
  - Better knowledge of nuclear structure and decay
  - Smaller uncertainties means more safety and/or higher cost efficiency for nuclear applications
- Expect a huge impact from Artificial Intelligence and Machine Learning in the coming decade

Thank you!